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13. ABSTRACT *(Maximum 200 words)*
A pc-based program was developed for design-oriented analysis of grid oscillator power combiners. The program was also extended to analysis of arbitrary cascaded quasi-optical active and/or passive components. Validation on passive unloaded gratings, passive loaded gratings and active gratings has been carried out and analysis agrees with measurements favorably. Grid oscillators designed using this theory have been implemented as sources in a two-level power-combining system consisting of a grid oscillator source and a lens amplifier combiner. Lens amplifiers can provide power gain with good feed efficiency, as well as beam-steering, beam forming and beam switching capabilities. Grid oscillators were also extended to a three-dimensional power combining source with power-combining efficencies above 70%. Injection-locking properties of grid oscillators were studied, and it was established that these components work well as self-oscillating harmonic and subharmonic mixers. This enables receivers which use quasi-optical components and do not require a separate LO. The heat dissipation in 2-D arrays was addressed by developing a high-efficiency amplifier array with 2.4W at 64% power-added efficiency at 5GHz.

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Grid oscillators – injection-locking, power design and modulation

Final Report

Zoya Popović

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A. Research goals

The goals of this research were to further the development of solid-state quasi-optical power combiners. We concentrated on both amplifier and oscillator combiners. In terms of the oscillators, the goal was to develop a theory that would allow generalized grid oscillator design in terms of both frequency and power. Another goal was to understand locking and modulation properties of these active quasi-optical sources. In terms of the amplifiers, the goal was to develop active antenna arrays with absolute power gain and beam-steering capabilities. These amplifiers are fed by grid oscillators to form a two-level power combining subsystem. Finally, experimental validation at microwave and millimeter-wave frequencies was an important objective in this project. All of the goals have been achieved, and some additional new and practical properties of quasi-optical active components have been demonstrated. The results are briefly described below.

B. Brief summary of research results

Grid oscillator modelling tool and validation – In quasi-optical grid oscillators, the output power of a large number of devices is combined in free space to produce a significant amount of power at microwave and millimeter wave frequencies. For specific grid geometries, the grid oscillator may be analyzed using the EMF method. However, the metal geometry significantly affects the operation of the grid, and also one might wish to place control devices, such as varactor diodes, on the back side of the dielectric (as in publication 1). In order to design a grid oscillator with optimum performance (e.g., tuning bandwidth, output power, etc.), it is important to be able to analyze a structure with arbitrary metallization on either one or both sides of the dielectric substrate. A pc-based Fortran program called GAP (Grid Analysis Program) for analyzing grid structures was developed based on a full-wave moment method approach. The program gives multiport s-parameters for an arbitrary metal geometry on one or both sides of an arbitrary dielectric substrate with a mirror placed at any distance behind the grids. Then the different ports of this network can be connected to any active devices (transistor, varactor, pin, Schottky diodes) and analyzed using a commercial circuit simulator and nonlinear analysis. In this way, we can optimize the performance of grid sources, while changing the following design parameters: active device lead orientation, type of control device, radiating metal geometry, dielectric thickness and permittivity and mirror position.

Passive grid structures for which reflection coefficient data are well known were analyzed to verify the theory behind the program. In this case, there is no device driving the current on the metallization. A plane wave is assumed to be incident on the metal pattern in free space without the dielectric slab present. The TEM component of the re-radiated electric field is computed from the current distribution, and the reflection coefficient is calculated. The metal pattern is modelled as a frequency-dependent shunt admittance which gives the same reflection coefficient in a $377\,\Omega$ transmission line, and the dielectric is modelled as a transmission line of the appropriate characteristic impedance and length. Reflection and transmission coefficients of this circuit are then calculated. As an example, this full-wave analysis was used to compute the reflection coefficient of an array of Jerusalem crosses, nested loops and inductive and capacitive gratings. The analysis compared favorably to measurements in all cases.

Several active grid oscillators were designed using GAP and fabricated with packaged HEMTs. They were designed for operation between 5 and 12 GHz and all operated within 6% of the design frequency. Related to this work, we have been working on power predictions from grid oscillators (this was funded by the AASERT program). By using GAP iteratively, we find the optimal imbedding impedance for a given device for maximum output power in saturation. In some cases, the optimal impedance cannot be provided by any grid shape or size, and lumped capacitors are needed. We have designed several grids optimized for power, and experimental validation is now in progress.

Quasi-optical subsystems or systems can be made by cascading quasi-optical components. We have extended our full-wave analysis tool (GAP) to analyze such cascaded systems. Theoretical results were confirmed by experiments on capacitively and resistively loaded grids with different metallization shapes.

Electrooptic sampling validation – A 25-HEMT grid oscillator was built on a GaAs electrooptic substrate, and the voltage distribution across the grid was measured using a unique electrooptic sampling technique as described in the original proposal. This technique gives the integral of the microwave electric field between the two sides of the dielectric substrate, and the measured complex voltages are referenced to the back surface. From the measured relative voltage amplitude and phase distribution, the current along the leads can be found by integrating the time derivative of the charge distribution. The 25-HEMT grid oscillator was designed using the model presented in (*Popović et al., IEEE MTT-39, No. 2, pp. 193–200*) to lock at around a 5.89 GHz frequency that corresponds to a multiple of the pulse repetition rate of the laser in the electrooptic sampling setup. The grid has a 5-mm period and is built on a 0.5-mm thick GaAs substrate, with the vertical leads being the radiating gate and drain leads, and the horizontal lines being the bias and source leads. The electrooptic sampling measurements showed that very little current flows in the bias lines and source leads, as expected, and that there is a large phase jump when going through the transistors. The measured potential distribution across the entire grid showed no substantial edge effects when the grid was quasi-optically injection-locked to an external synthesized source.

Lens amplifiers and two-level power combiners – two lens amplifier arrays were demonstrated: a transmitting patch-MESFET 28-element array with 8 dB gain at 10 GHz and a low-noise receiving PHEMT slot array with 13 dB absolute power gain and 1.9 dB noise figure in a 1-GHz bandwidth at 10 GHz. A PHEMT grid oscillator was designed to operate at 10.25 GHz as a focal-point feed to a free-space amplifier array. By moving the grid source along a focal arc of the lens, beam steering up to 45 degrees in both planes with less than 2 dB power variation in the main lobe was observed. Two such identical grids were designed using GAP, they both operated at the designed frequency and at equal power levels and were used for successful beam-forming and beam-switching experiments (see publications 4 and 6).

Three-dimensional grid oscillators – Grid oscillators can be cascaded in the radiation direction. The power grows linearly as the number of grids is increased. Up to four grids were combined at 5 GHz, showing a 70-% power combining efficiency. The advantage of this approach is that the power is distributed between several active surfaces and the heat

removal is facilitated as compared to a single larger grid.

Grid-oscillators as self-oscillating mixers – One type of quasi-optical mixer that has been demonstrated is a diode-loaded grid. A receiver using this type of component requires a separate LO. Alternatively, one can use a self-oscillating mixer, in which a single device generates the LO and mixes it with the RF signal. We have demonstrated a 25-PHEMT grid functioning as a self-oscillating mixer.

The 25-element grid is the same as the one used in the 3-D combiners described above, and has a free-running oscillation frequency of 5.36 GHz. A vertically polarized RF signal incident on the grid is received by the vertically oriented drain and gate leads of the grid oscillator and mixes with the LO. The IF signal is detected from the horizontally oriented DC bias lines. The horizontal lines contain very little of the RF and LO signals, so this scheme provides a simple method of isolating these signals from the IF. Since the grid does not provide RF-LO isolation, the oscillator will work as a self-oscillating mixer only if the RF signal is outside of its injection-locking range. The grid can also serve as a subharmonic self-oscillating mixer by using the second harmonic as the LO. This type of mixer has a distinct advantage in millimeter-wave receivers where it may be difficult to build an LO at the fundamental frequency. Since the second harmonic level of the grid oscillator is approximately −30 dBc, the IF power is much lower for the subharmonic case.

High-efficiency active array amplifiers – Efficiency is a very important factor for quasi-optical components, especially amplifiers, due to the 2-D nature of the devices. If the efficiency is increased from, say 50% to 75%, the heat-sinking is decreased by a factor of three. For example, we have designed a 30-GHz array which was built and measured by Lockheed Martin, Orlando, and demonstrated 2 W at 30 GHz with 10% efficiency. This is the highest millimeter-wave power demonstrated to date in a quasi-optical amplifier, but due to the low efficiency, the 9 W of heat caused the substrate to crack. We have been working on a class-E high-efficiency amplifier design and have demonstrated a 4-element MESFET slot antenna array with 2.4 W output power, 71% drain efficiency and 64% power-added efficiency at 5 GHz. These are by far the highest efficiency numbers obtained in any quasi-optical device so far and show promise for high-power amplifiers not limited by heat sinking.

C. Publications

The following publications resulted from research done fully or partially funded by this grant. The semiannual technical reports are not listed.

JOURNAL PUBLICATIONS

1. "Quasi-Optical VCOs," S. Bundy, T. Mader, Z.B. Popović, *IEEE Transactions on Microwave Theory and Techniques, Special Issue* October 1993.

2. "Planar MESFET Transmission Wave Amplifier," T. Mader, J. Schoenberg, L. Harmon, Z. B. Popović, *IEE Electronic Letters, Vol. 28, No. 19*, pp. 1699–1701, September 1993.

3. "A 100-transistor quadruple grid oscillator," W. A. Shiroma, B. L. Shaw, Z. B. Popović, *IEEE MTT Microwave and Guided Wave Letters, Vol.4, No.10*, pp. 350–352, October 1994.

4. "Two-level power combining using a lens amplifier," J. S. H. Schoenberg, S. C. Bundy, Z. B. Popović, *IEEE Transactions on Microwave Theory and Techniques, Vol.42, No.12*, pp. 2480–2485, December 1994.

5. "A generalized analysis for grid oscillator design," S. C. Bundy, Z. B. Popović, *IEEE Transactions on Microwave Theory and Techniques, Vol.42, No.12*, pp. 2486–2491, December 1994.

6. "The transmission-line high-efficiency class-E amplifier," T.B. Mader, Z. B. Popović, *IEEE MTT Microwave and Guided Wave Letters, Vol.5, No.10*, October 1995.

7. "Cascaded active and passive quasi-optical grids," W. Shiroma, S. Bundy, S. Hollung, B. Bauernfiend, Z.B. Popović, *to be published in the IEEE Trans. on Microwave Theory and Techniques,* December 1995.

CONFERENCE AND WORKSHOP DIGEST PAPERS

1. "Quasi-Optical Array VCO's," T. Mader, S. Bundy, Z. B. Popović, *1992 IEEE International Microwave Symposium Digest*, pp. 1539–1543.

2. "Optical Measurements of Microwave Grid Oscillator Power Combiners," K.Y. Chen, P.D. Biernacki, A.R. Mickelson, Z.B. Popović, *IEEE MTT International Symposium Digest*, pp.313–316, Atlanta, June 1993.

3. "Design-Oriented Analysis of Grid Power Combiners," S. Bundy, W. Shiroma, Z.B. Popović, *presented at the Workshop on Millimeter-Wave Power Generation and Beam Control*, Huntsville, Alabama, September 1993.

4. "Three-dimensional power combiners," W. A. Shiroma, B. L. Shaw, Z. B. Popović, *IEEE MTT International Symposium Digest*, pp. 831–834, San Diego, May 1994.

5. "Analysis of planar grid oscillators," S. C. Bundy, Z. B. Popović, *IEEE MTT International Symposium Digest*, pp. 827–830, San Diego, May 1994.

6. "Quasi-optical antenna array amplifiers," J. Schoenberg, T. Mader, B. Shaw, Z.B. Popović, *1995 IEEE MTT-S Int. Symp. Dig. (Orlando, FL)*, pp. 605–608, May 1995.

7. "Analysis of cascaded quasi-optical grids," S.C. Bundy, W.A. Shiroma, Z.B. Popović, *1995 IEEE MTT-S Int. Symp. Dig. (Orlando, FL)*, pp.601–604, May 1995.

8. "High-efficiency amplifiers for portable handsets," T. Mader, M. Markovic, Z.B. Popović, *6th International Symposium on Personal, Indoor and Mobile Radio Communications, PMIRC 95, Digest* pp. September 1995, Toronto.

9. "Quasi-optical components and subsystems for communications," Z. Popović *Invited paper, ISSSE* October 1995, San Francisco.

10. "A quasi-optical receiver with angular diversity," W. Shiroma, S. Hollung, E. Bryerton, Z.B. Popović, *submitted to the 1996 IEEE MTT-S International Symposium*, June 1996, San Francisco.

D. Earned degrees

Two students, Scott Bundy and Thomas Mader, have earned their doctorates and were partially funded by this grant. Dr. Bundy is now with SCT, Inc. in Golden, Colorado as leading research engineer, and Dr. Mader is with Hughes Airospace, El Segundo, California. Their thesis titles are listed below. Thomas Mader's thesis is attached to the report.

1. Scott Christopher Bundy, *Analysis and Design of Grid Oscillators*, Ph.D. Thesis, University of Colorado, 1994.
2. Thomas Bruno Mader, *Quasi-Optical Class-E Power Amplifiers*, Ph.D. Thesis, University of Colorado, 1995.